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Single and Multiple Tuned Liquid Column Dampers for Seismic Applications

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Building and Fire Research Laboratory
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U.S. Department of Commerce
Michael Kantor, *Secretary*
Technology Administration
Mary L. Good, *Under Secretary for Technology*
National Institute of Standards and Technology
Arati A. Prabhakar, *Director*

ABSTRACT

The optimum parameters of single and multiple tuned liquid column dampers (TLCD) for reducing the response of structures to seismic loads are presented. A deterministic analysis is carried out using 72 earthquake ground motion records to determine the optimum tuning ratio, tube width to liquid length ratio, and head loss coefficient corresponding to a given mass ratio for single tuned liquid column dampers (STLCD). A similar analysis is performed to determine the optimum central tuning ratio, tuning bandwidth, and grouping of dampers for multiple tuned liquid column dampers (MTLCD). The optimum parameters are used to compute the response of several single-degree-of-freedom structures and one multi-degree-of-freedom structure with single and multiple TLCDs to different earthquake excitations. The study indicates that: a) the use of the optimum parameters reduces the displacement and acceleration responses; b) MTLCDs have a slight advantage over STLCDs in reducing the response; and c) MTLCDs are robust to errors in estimating the structural parameters. The solution from an analysis using TLCDs is compared with that using tuned mass dampers where it is found that both devices result in comparable reductions in the response. Design examples using STLCDs and MTLCDs in a simple bridge model and in a ten-story structure are presented to illustrate how the parameters are selected and demonstrate the performance of the devices under different ground excitations.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Tuned liquid dampers (TLD) and tuned liquid column dampers (TLCD) are passive energy absorbing devices that have been suggested for controlling vibrations of structures under different dynamic loading conditions. TLDs consist of rigid tanks filled with shallow liquid where the sloshing motion absorbs the energy and dissipates it by the viscous action of the liquid, wave breaking, and auxiliary damping appurtenances such as baffles, nets or floating beads. TLCDs consist of tube-like containers filled with liquid where energy is dissipated by the movement of the liquid through an orifice. Both devices have proved effective in reducing the response of structures to wind excitations (Kwok *et al.*, 1991; Xu *et al.*, 1992; Fujino and Sun, 1993; Kareem, 1994) and have been installed in structures. Examples include: the 149.4 m-high Shin Yokohama Prince Hotel in Japan (Kareem, 1994) with 30 TLDs attached to the top floor; and the Higashi-Kobe cable-stayed bridge in Japan (Sakai *et al.*, 1991) with TLCD units attached to the bridge deck. For seismic applications, however, sufficient studies have not been carried out to assess the effectiveness of these devices in reducing the structural response.

TLCDs are relatively easy to install in new and existing buildings. They do not interfere with vertical and horizontal load paths as other passive devices do. It is easy to adjust their frequencies, and they can be combined with active control mechanisms (Haroun *et al.*, 1994a, 1994b; Kareem, 1994) to function as hybrid systems. Unlike tuned mass dampers, TLCDs do not require a large space for stroke lengths. Furthermore, as Kareem (1994) has demonstrated, TLCDs can be used to dissipate energy in two directions by using a bi-directional U-tube. The configuration consists of partitioning the container with a block that results in stacked U-tubes in both directions with a common base.

In this study, the effectiveness of single and multiple tuned liquid column dampers (STLCD and MTLCD) for seismic applications is examined. The response of several single-degree-of-freedom structures with TLCDs to 72 earthquake accelerograms is computed and used to determine the optimum parameters (tuning ratio, tube width to liquid length ratio, and head loss coefficient) for STLCDs and (central tuning ratio, tuning bandwidth, and grouping of dampers) for MTLCDs. Two design examples -- a bridge girder modeled as a single-degree-of-freedom structure and a ten-story structure, each equipped with STLCD and MTLCD -- are used to illustrate the selection of the optimum parameters and their effectiveness in reducing the response to earthquake loading.

2. ANALYSIS

A tuned liquid column damper attached to a single-degree-of-freedom (SDOF) system is shown in figure 2.1. The equation of motion of the liquid column is (Sakai *et al.*, 1989):

$$\rho AL\ddot{y} + \frac{1}{2}\rho A\delta|\dot{y}|\dot{y} + 2\rho Agy = -\rho AB\ddot{x} \tag{2.1}$$

where A, B, L, ρ, and g are the cross sectional area of the tube, tube width, liquid column length, liquid density, and acceleration due to gravity, respectively. The head loss coefficient δ depends on the orifice opening ratio (area of opening/cross-sectional area of tube) where $\delta = 0$ corresponds to full orifice opening and $\delta = \infty$ signifies full orifice closure. The value of δ in terms of the orifice opening ratio can be found in Blevins (1984), or from experiments for specific orifice shapes and sizes. In the above equation, y represents the elevation change of the liquid column and x the horizontal movement of the tube which is the same as that of the structure.

Recalling the equation of motion of a tuned mass damper (TMD) subjected to ground acceleration $\ddot{x}_g$ given by

$$\ddot{z} + 2\xi\omega\dot{z} + \omega^2 z = -\ddot{x}_g \tag{2.2}$$

where ξ is the damping ratio and ω the natural frequency of the TMD and comparing it with equation (2.1), it can be shown that a tuned liquid column damper can be considered as a tuned mass damper with a natural frequency ω_t given by

$$\omega_t = \sqrt{\frac{2g}{L}} \tag{2.3}$$

and a velocity-dependent damping ratio ξ expressed as

$$\xi = \frac{\delta}{4\sqrt{2gL}}|\dot{y}| \tag{2.4}$$

For a SDOF structure with mass M, natural frequency ω_o, and damping ratio β with a TLCD (Fig. 1.1), the equations of motion of the system subjected to ground acceleration $\ddot{x}_g$ are

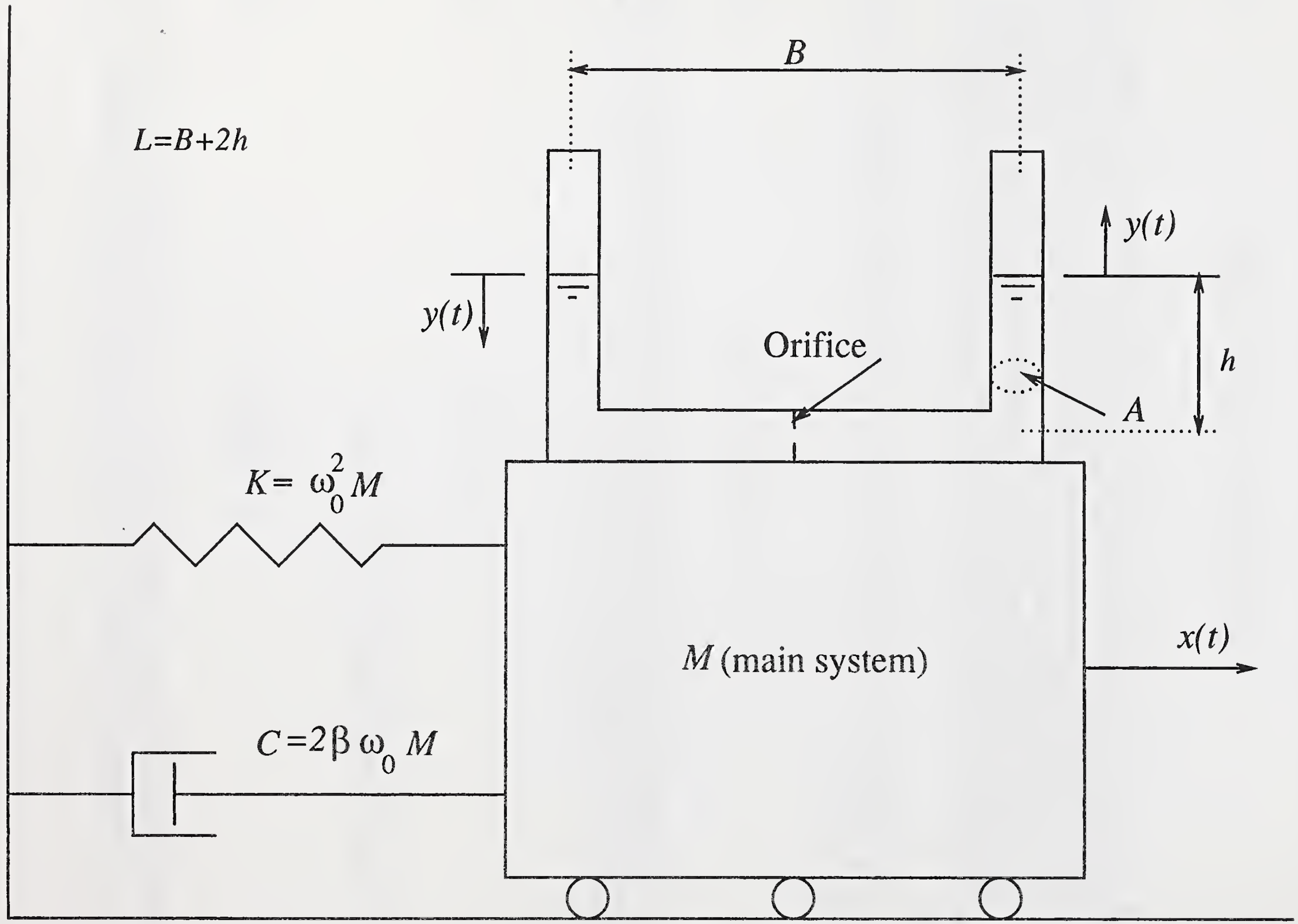

Figure 2.1 Tuned liquid column damper mounted on a main structure

$$\begin{bmatrix} M+\rho AL & \rho A\alpha L \\ \rho A\alpha L & \rho AL \end{bmatrix}\begin{Bmatrix} \ddot{x} \\ \ddot{y} \end{Bmatrix}+\begin{bmatrix} 2M\omega_o\beta & 0 \\ 0 & \frac{1}{2}\rho A\delta|\dot{y}| \end{bmatrix}\begin{Bmatrix} \dot{x} \\ \dot{y} \end{Bmatrix}+\begin{bmatrix} M\omega_o^2 & 0 \\ 0 & 2\rho Ag \end{bmatrix}\begin{Bmatrix} x \\ y \end{Bmatrix}=-\begin{Bmatrix} M+\rho AL \\ \rho A\alpha L \end{Bmatrix}\ddot{x}_g \tag{2.5}$$

where $\alpha = B/L$ is the ratio of the tube width to the liquid length. The presence of the term $|\dot{y}|$ in equations (2.1) and (2.4) indicates that TLCDs have a nonlinear behavior. Xu *et al.* (1992) and Kwok *et al.* (1991) used the method of equivalent linearization to solve the nonlinear equations. They used a stochastic procedure to compute an equivalent damping coefficient c_p by minimizing the difference between equation (2.1) and the equation of a SDOF system with a damping coefficient c_p. The equivalent damping is found to be

$$c_p = \frac{\sigma_{\dot{y}}\delta}{\sqrt{2\pi}} \tag{2.6}$$

where $\sigma_{\dot{y}}$ is the standard deviation of the liquid elevation velocity $\dot{y}$. Xu *et al.* (1992) and Kwok *et al.* (1991) computed the mean square response of structures with TLCDs to a zero-mean stationary Gaussian wind excitation. Since $\sigma_{\dot{y}}$ is not known *a priori,* they used an iterative procedure to solve the equations. In a later study, Sun (1994) used the same linearization technique to arrive at the mean square response of a SDOF structure with a TLCD to a stationary Gaussian ground acceleration to examine the effectiveness of the device for seismic applications. Instead of using an iterative procedure, Sun proposed simplified approximate equations to compute the response.

The equivalent linearization method can not be used for a deterministic analysis since a closed form solution for a SDOF structure subjected to a digitized earthquake ground acceleration is not available. An iterative procedure is, therefore, used herein to compute the response. The method consists of estimating the liquid elevation velocity $\dot{y}$ at each time increment by using the first two terms in a Taylor series expansion, i.e.

$$\dot{y}_{est}(t) = \frac{5}{2}\dot{y}(t-\Delta t) - 2\dot{y}(t-2\Delta t) + \frac{1}{2}\dot{y}(t-3\Delta t) \tag{2.7}$$

Using the estimated value of $\dot{y}$, the damping term $\rho A\delta|\dot{y}|/2$ of the TLCD and consequently, the response of the structure with the TLCD (*x, y,* and their derivatives) is computed by solving equation (2.5). The difference between the estimated $\dot{y}_{est}$ and computed $\dot{y}_{com}$ is then calculated. If the relative error $|(\dot{y}_{est} - \dot{y}_{com})/\dot{y}_{com}|$ is greater than a desired tolerance (10^{-6} in this study), the procedure is repeated using $\dot{y}_{com}$ as $\dot{y}_{est}$ until convergence is obtained. The method was examined for different ground excitations and found that usually one to three iterations were sufficient to achieve convergence.

3. OPTIMUM PARAMETERS OF SINGLE TUNED LIQUID COLUMN DAMPERS

The term single tuned liquid column damper (STLCD) refers to one or several tuned liquid column damper (TLCD) units with identical parameters. In addition to α and δ, the other parameters of a STLCD may be defined in terms of its tuning ratio f and mass ratio μ as

$$f = \frac{\omega_t}{\omega_o} = \frac{\sqrt{\frac{2g}{L}}}{\omega_o} \tag{3.1}$$

and

$$\mu = \frac{\rho A L}{M} \tag{3.2}$$

The optimum parameters f, α, and δ for a given mass ratio μ are determined from the response of a number of SDOF structures with different f, α, and δ to a set of 72 horizontal components of accelerograms from 36 stations in the western Unites States (Appendix A). These accelerograms include a range of earthquake magnitudes (5.2 to 7.7), epicentral distances (6 km to 127 km), peak ground accelerations (0.044 g to 1.172 g), and two soil conditions (rock and alluvium). The relative displacement and absolute acceleration response ratios were computed as the ratio of the peak response of the structure with a STLCD to the peak response without a STLCD. The optimum parameters were identified as those which resulted in the lowest mean response ratio.

3.1 Scaling of External Excitation

It is noted from equation (2.1) that the damping in a TLCD depends on the liquid velocity $\dot{y}$ and therefore, on the external excitation. Because accelerograms have different peak ground motions, they cannot be used on an absolute basis in a statistical analysis. In such cases, the records are scaled to a common denominator (same acceleration, velocity, or displacement) before they are used in the analysis. To determine which ground motion parameter (velocity or acceleration*) is most suitable as a scaling parameter, 30 SDOF structures with a 2 percent damping and periods ranging from 0.1 s to 3.0 s with increments of 0.1 s were analyzed with and without STLCDs. The following typical STLCD parameters were considered: $\mu = 0.02$, $f = 1$, $\alpha = 0.7$, and $\delta = 0.5$. The 72 records were scaled to a maximum ground acceleration $a = 0.25g$ and to a maximum ground velocity $v = 0.30$ m/s. The coefficients of variation COV (the standard deviation divided by the mean) for the displacement and acceleration response ratios were computed and plotted in figure 3.1. The figure shows that the COVs for records scaled to peak ground velocity are slightly smaller than that for records scaled to acceleration. The difference between the two COVs, however, is not significant and since the ground acceleration is usually the most readily available ground motion data, it was used as the scaling parameter.

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* Because of the errors inherent in baseline adjustment, displacements are seldom used as a scaling parameter.

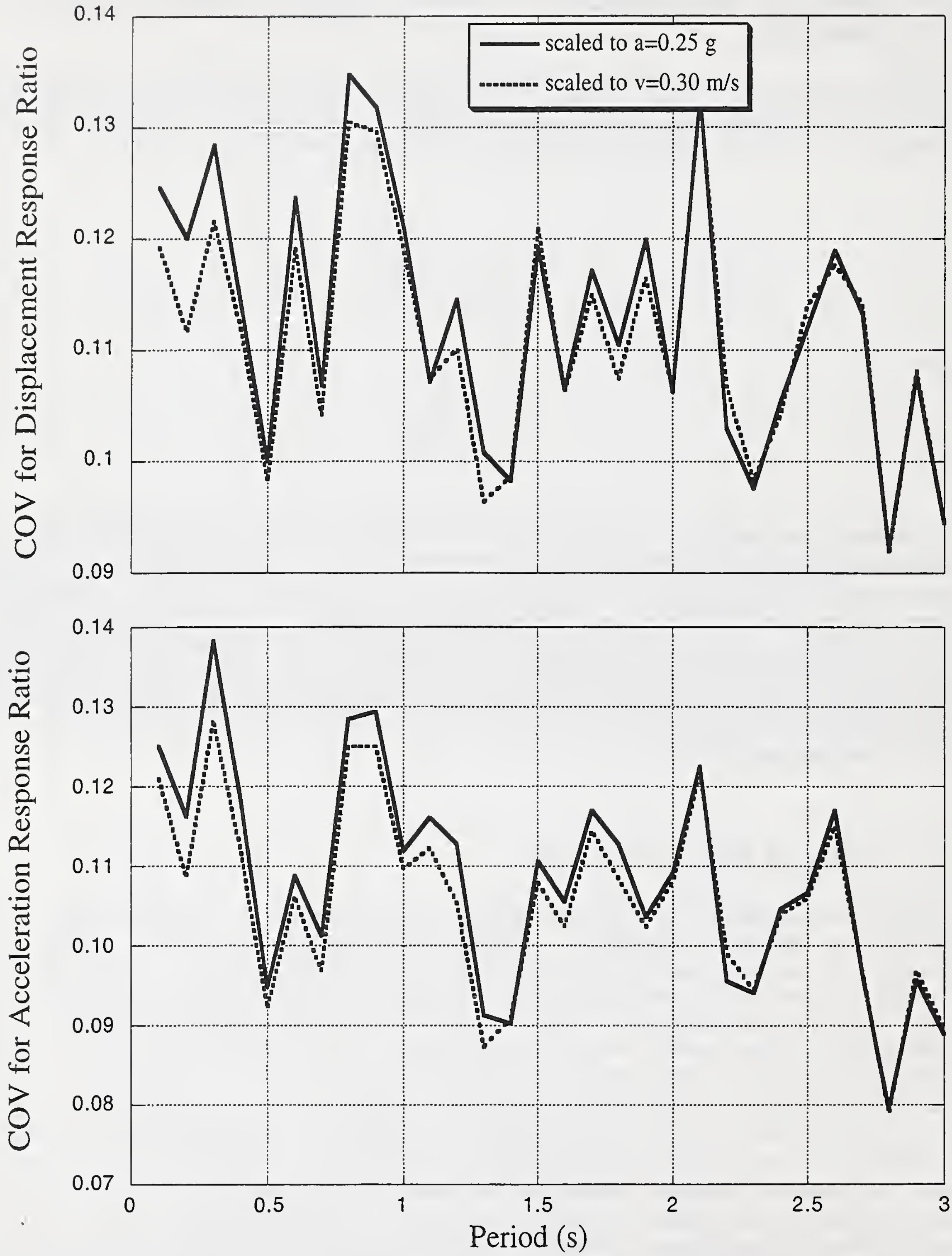


Figure 3.1 Variation of the coefficient of variation (COV) for response reductions of SDOF structures of $\beta = 0.02$ with STLCD of $\mu = 0.01, f = 1.0$, and $\delta = 0.5$

The optimum parameters (f, α, and δ) are determined for four mass ratios μ = 0.005, 0.01, 0.02, and 0.04; and two damping ratios β = 0.02 and 0.05. To obtain the optimum value of each parameter, the influence of that parameter on the response of a SDOF system with a natural period T = 1.0 s with a STLCD is determined by varying that parameter while keeping the other two constant.

3.2 Optimum Tuning Ratio f

To determine the optimum f, a typical tube width to liquid length ratio α = 0.7 and a head loss coefficient δ = 0.5 were considered. The accelerograms were scaled to a peak ground acceleration $a = 0.25\,g$. Tuning ratios f ranging from 0.8 to 1.2 with increments of 0.1 were used in the analysis. The mean displacement and acceleration response ratios for the four mass ratios are shown in figure 3.2 which show that the higher the mass ratio for a STLCD, the better its performance (lower response). Similar to tuned mass dampers, the optimum tuning ratio f_{opt} depends not only on the mass ratio but also on the damping in the structure. Based on the results in figure 3.2 and the range of mass and damping ratios considered in this study, the optimum tuning ratio is found to be very close to the tuning ratio of TMDs for a white noise ground acceleration given by Warburton (1982) as

$$f_{opt} = \frac{\sqrt{1 - \frac{\mu}{2}}}{1 + \mu} \tag{3.3}$$

Equation (3.3) does not reflect the damping of the structure β. Tuning ratios for different structural damping coefficients may be obtained from Warburton (1982).

3.3 Optimum Tube Width to Liquid Length Ratio α

To obtain the optimum α, a head loss coefficient δ = 0.5 and the optimum tuning ratio f_{opt} computed from equation (3.3) were considered. The 72 records scaled to a peak ground acceleration $a = 0.25\,g$ were used in the analyses. The analyses were carried out for values of α ranging from 0.1 to 0.9 with increments of 0.05. The results are presented in figure 3.3 where it is observed that the larger the α, the larger the response reduction. Sun (1994) reported that increasing α increases the root mean square displacement of the structure. This study, however, suggests (see figure 3.3) that α should be as large as possible as long as liquid is retained in the horizontal portion of the U tube. If y_{max} is the anticipated maximum change in liquid elevation, then,

$$\alpha_{opt} = 1 - 2\frac{|\, y_{max} \,|}{L} \tag{3.4}$$

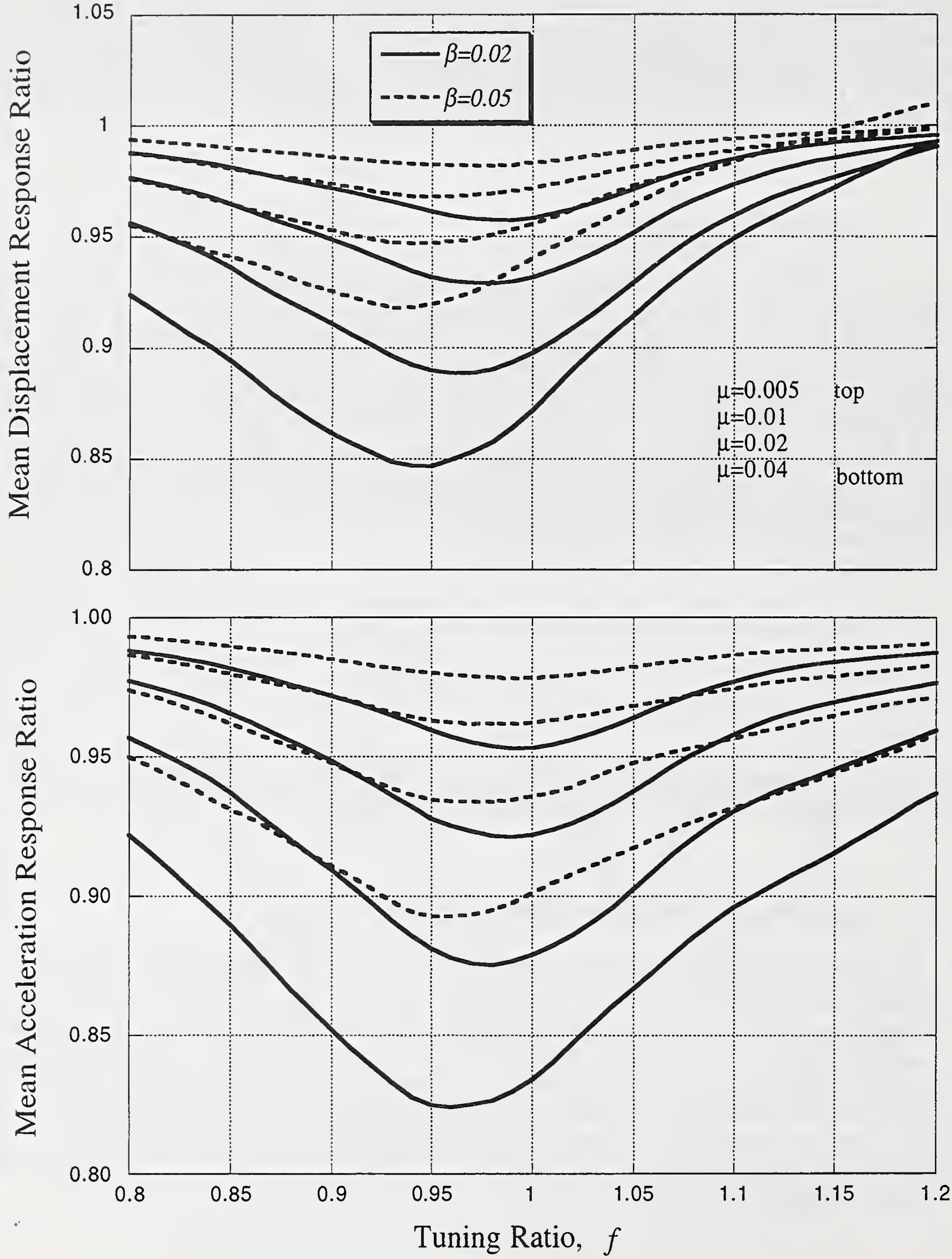


Figure 3.2 Variation of mean response ratios with tuning ratios f for different structural damping ratios and STLCD mass ratios

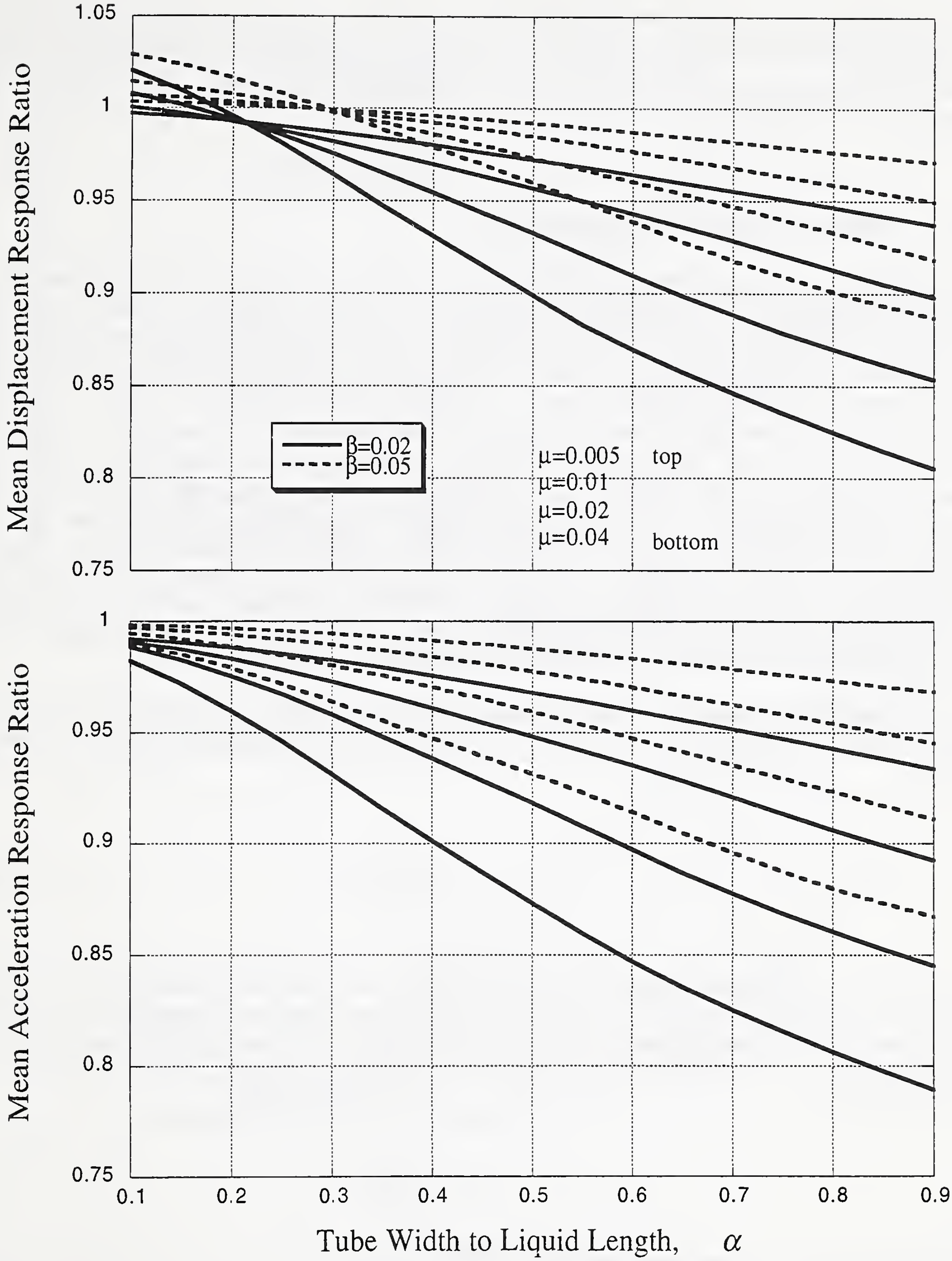


Figure 3.3 Variation of mean response ratios with liquid length to tube width α

An iterative procedure was used to determine α_{opt} since $y_{\max}$ depends on the excitation level. Based on different analyses, a value of α_{opt} between 0.75 to 0.80 was determined appropriate for moderate to strong ground motions (accelerations up to 0.7 g). An α_{opt} = 0.8 is used in this study.

3.4 Optimum Head Loss Coefficient δ

For a tuned mass damper, the optimum damping ratio ξ is a function of the mass ratio μ and structural damping ratio β (Warburton, 1982; Villaverde, 1985; Sadek *et al.*, 1996). From the similarity between TMD and TLCD, it may be concluded from equation (2.4) that the head loss coefficient δ not only depends on β and μ but also on $\dot{y}$ or ground excitation. To determine the optimum δ, a SDOF structure (T=1.0 s, β=0.02) with a STLCD (μ = 0.02, α = 0.8, $f = f_{opt}$) was subjected to the 72 earthquake accelerograms scaled to acceleration levels of 0.05, 0.10, 0.25, 0.50, 0.75, and 1.00 g. The head loss coefficient δ was varied from 0.1 to 100 with four equally spaced intervals in each logarithmic cycle. The mean displacement and acceleration response ratios were computed and plotted in figure 3.4 which show that the same reduction in the response can be obtained for different ground excitation levels by using an appropriate δ for the excitations. Haroun *et al.* (1994) have indicated that for the peak displacement reduction, δ should be 0.4 and for the RMS displacement reduction, δ should be 0.8 regardless of the peak ground acceleration. This study, however, suggests (Fig. 3.4) that for best reduction δ should vary according to the expected ground acceleration.

The procedure was repeated with different mass and damping ratios and it was found that for a given mass and damping ratio, the product of δ_{opt} and ground acceleration remains a constant. Thus,

$$\delta_{opt}\left(\frac{a}{g}\right) = \eta \tag{3.5}$$

where η is a constant that depends on the mass ratio μ and structural damping ratio β. For the range of mass and damping ratios considered herein, η was found to be dependent more on the mass ratio than the damping ratio as shown in figure 3.5. To obtain a simple expression of estimating η, η was computed in terms of the mass ratio μ using the best fit on the data. It was found that

$$\eta = 3.58\mu \tag{3.6}$$

Therefore, for the maximum displacement reduction, the optimum head loss coefficient can be obtained from equations (3.5) and (3.6) as

$$\delta_{opt} = \frac{3.58\mu}{a/g} \tag{3.7}$$

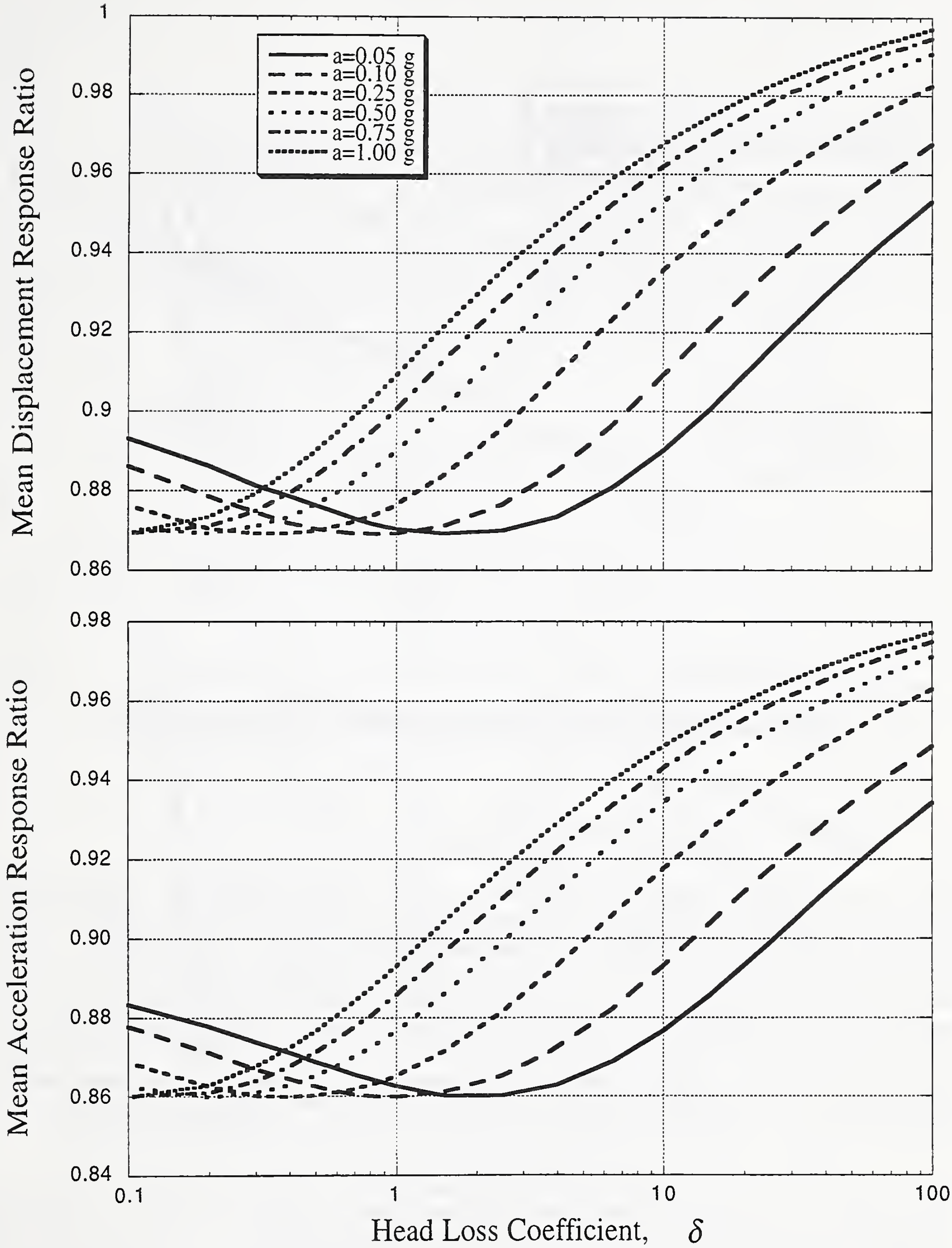


Figure 3.4 Variation of mean response ratios with head loss coefficient δ

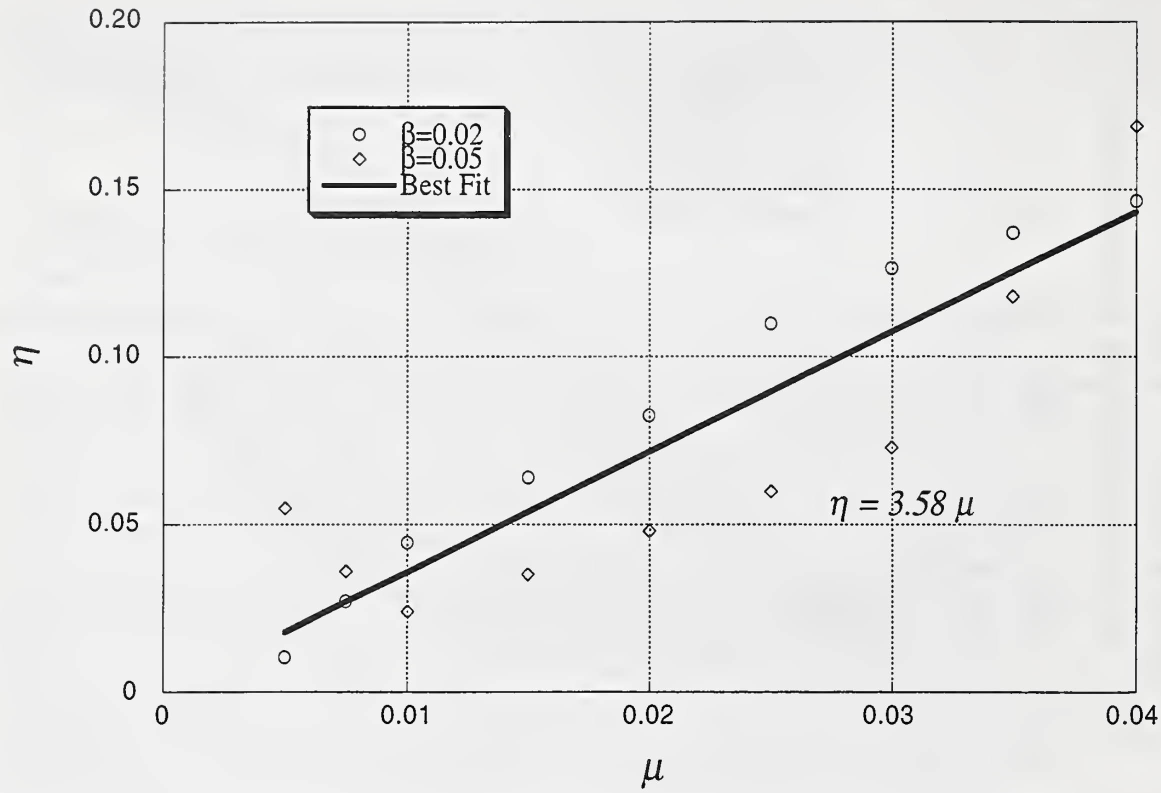


Figure 3.5 Relationship between the constant η and the mass ratio μ

3.5 Selection of Optimum Parameters

From the previous analyses, the selection of optimum parameters for STLCDs may be summarized as follows: the mass ratio μ should be determined based on the trade-off between the desired reduction in the response and the cost, space, and weight of the dampers. Once the mass ratio is selected, the tuning ratio f and the head loss coefficient δ which depends on the anticipated ground acceleration at the site can be determined from equations (3.3) and (3.7), respectively. The tuning ratio is used to find the liquid length L from equation (3.1) and the head loss coefficient is used to obtain the orifice opening (Blevins, 1984). Using α=0.8 as suggested previously, the tube width B can be determined. For structures with large masses, it is practical to use several tubes to achieve the desired mass ratio. The cross-sectional area of the individual tubes is computed from equation (3.2) by dividing A by the number of units.

This method was used to select the STLCD parameters for SDOF structures with periods between 0.1 to 3.0 s with increments of 0.1 s, mass ratios of 0.005, 0.01, 0.02, and 0.04, and damping ratios of 0.02 and 0.05. The ground excitations included the 72 accelerograms scaled to a peak ground acceleration of 0.25 g. The mean displacement and acceleration response ratios are shown in figure 3.6 where it is observed that reductions in displacements and accelerations may be achieved using TLCDs, particularly for structures with small damping ratios. Increasing the mass ratio results in a higher damping in the system and consequently in a better response reduction.

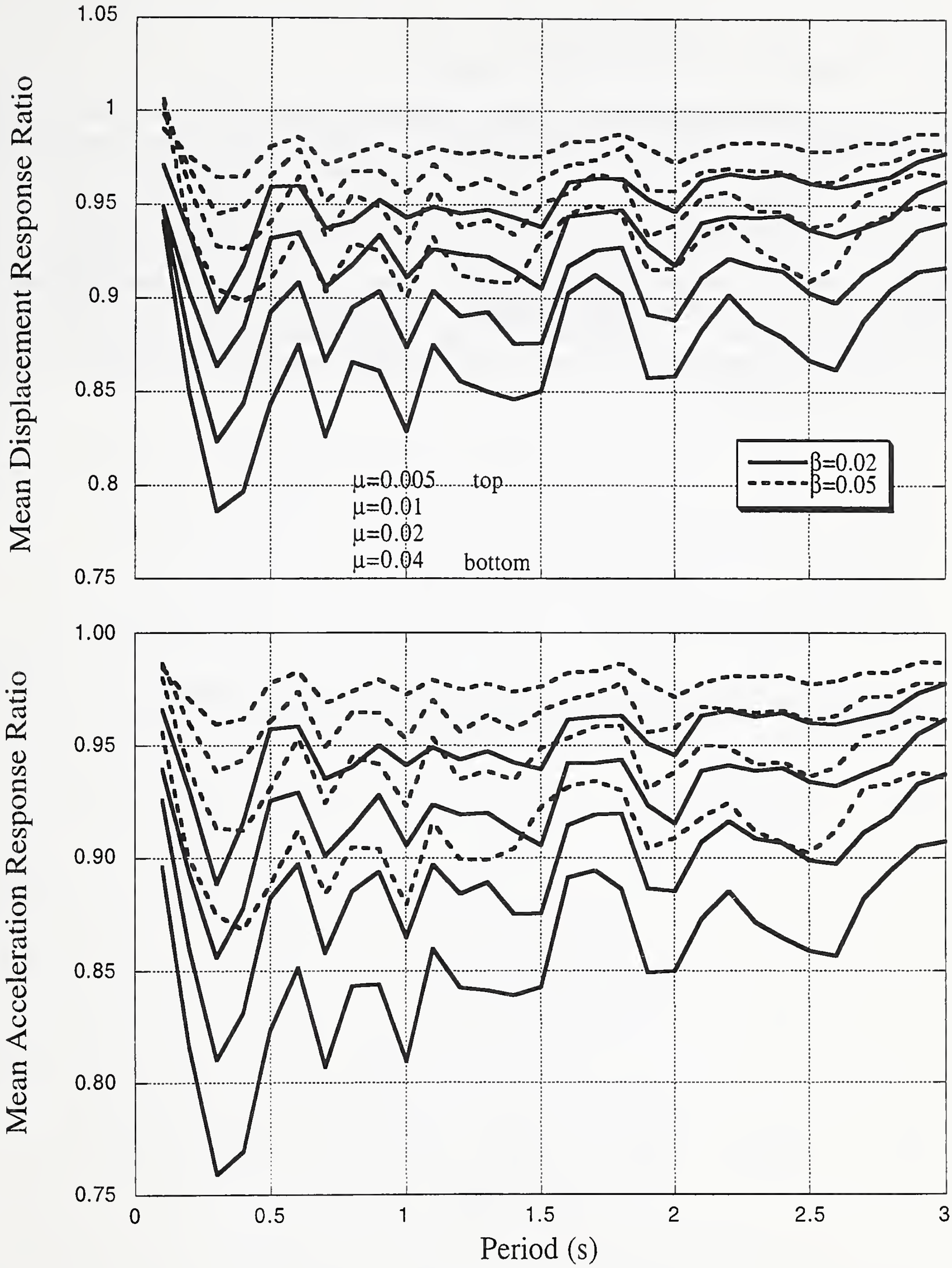


Figure 3.6 Mean response ratios for SDOF structures with STLCDs

3.6 Comparison with Tuned Mass Dampers

Sadek *et al.* (1996) used an analysis similar to that presented in the previous section for SDOF structures with tuned mass dampers. A comparison of their results for TMDs and those for TLCDs is shown in figure 3.7 for the 30 SDOF structures with a damping ratio $\beta = 0.02$. The responses with TMDs are normalized to those with TLCDs for two mass ratios $\mu = 0.02$ and 0.04. The figure indicates that similar reductions in the response are obtained with both TLCD and TMD for identical mass ratios. TLCDs, however, have the following advantages over TMDs: a) they do not require large stroke lengths; b) it is easy to tune their frequency by adjusting their liquid column length L; and c) they are capable of providing control in two directions simultaneously. On the other hand, the small densities of water or other fluids in TLCDs relative to those of steel, concrete, or lead in TMDs necessitates larger spaces to produce the same damping effect.

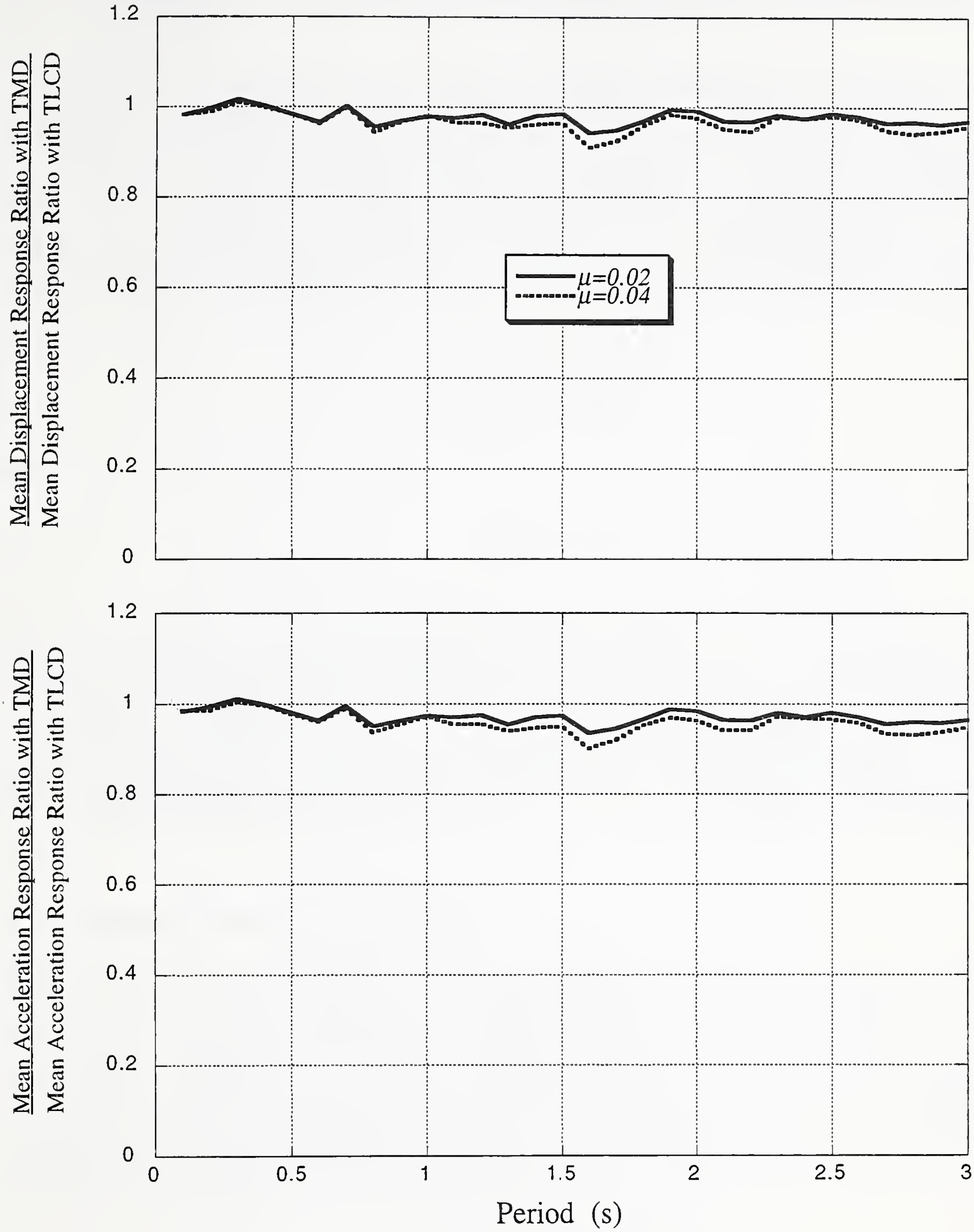


Figure 3.7 Comparison of mean displacement and acceleration response ratios for SDOF structures with TMDs and TLCDs for a damping ratio $\beta = 0.02$

4. OPTIMUM PARAMETERS OF MULTIPLE TUNED LIQUID COLUMN DAMPERS

The term multiple tuned liquid column damper (MTLCD) refers to several TLCD groups, each group with a different set of design parameters. The number of units in each TLCD group may range from one to several hundreds in order to meet the required liquid mass. In this study, the same tube proportion α, cross-sectional area A, liquid density ρ, and head loss coefficients δ are used for each group. The only variable is the liquid length L which influences the tuning ratio f_i, see equation (3.1). The difference between two adjacent tuning ratios ($f_{i+1} - f_i$) is assumed constant. Referring to figure 4.1, the system may be characterized in terms of its central tuning ratio f_0, tuning bandwidth Δf, and the number of TLCD groups N, where

$$f_0 = \frac{f_N + f_1}{2} \tag{4.1}$$

and

$$\Delta f = \frac{f_N - f_1}{f_0} \tag{4.2}$$

Once the tuning ratio f_i for each group is determined, the liquid length L_i can be computed from equation (3.1) and the tube cross-sectional area A_i from equation (3.2) by substituting $\sum L_i$ for L. Analyses were carried out for α = 0.8 and δ_{opt} computed from equation (3.7) using the total mass ratio of all units. The mean response ratios were computed using the same 72 accelerograms scaled to a peak ground acceleration of 0.25 g. Parametric studies were carried out to determine the influence of the parameters Δf, N, and f_0 on the MTLCD performance.

4.1 Optimum Tuning Bandwidth Δf

A SDOF structure with a period T = 1.0 s and damping ratio β = 0.02, with seven TLCD groups was considered in determining the influence of Δf. Mass ratios of 0.005, 0.01, 0.02, and 0.04 and a central tuning ratio f_0 = 1.0 were assumed. The tuning bandwidth Δf was varied from 0 (STLCD) to 0.4 with increments of 0.02. The mean displacement and acceleration response ratios are shown in figure 4.2 which indicate that a better reduction in response is obtained for a Δf other than zero. The optimum Δf values for displacement reduction were found to be 0.125, 0.10, 0.05, and 0.025 for mass ratios of 0.04, 0.02, 0.01, and 0.005, respectively.

4.2 Optimum Number of TLCD Groups N

To find the optimum number of TLCD groups, the SDOF structure used previously was also used herein with different TLCD groups. The optimum tuning bandwidths from figure 4.2 and a central tuning ratio f_0 = 1.0 were used in the analysis. The number of TLCD groups N was varied from 1 (STLCD) to 31. The results are shown in figure 4.3 which indicate that N=5 is

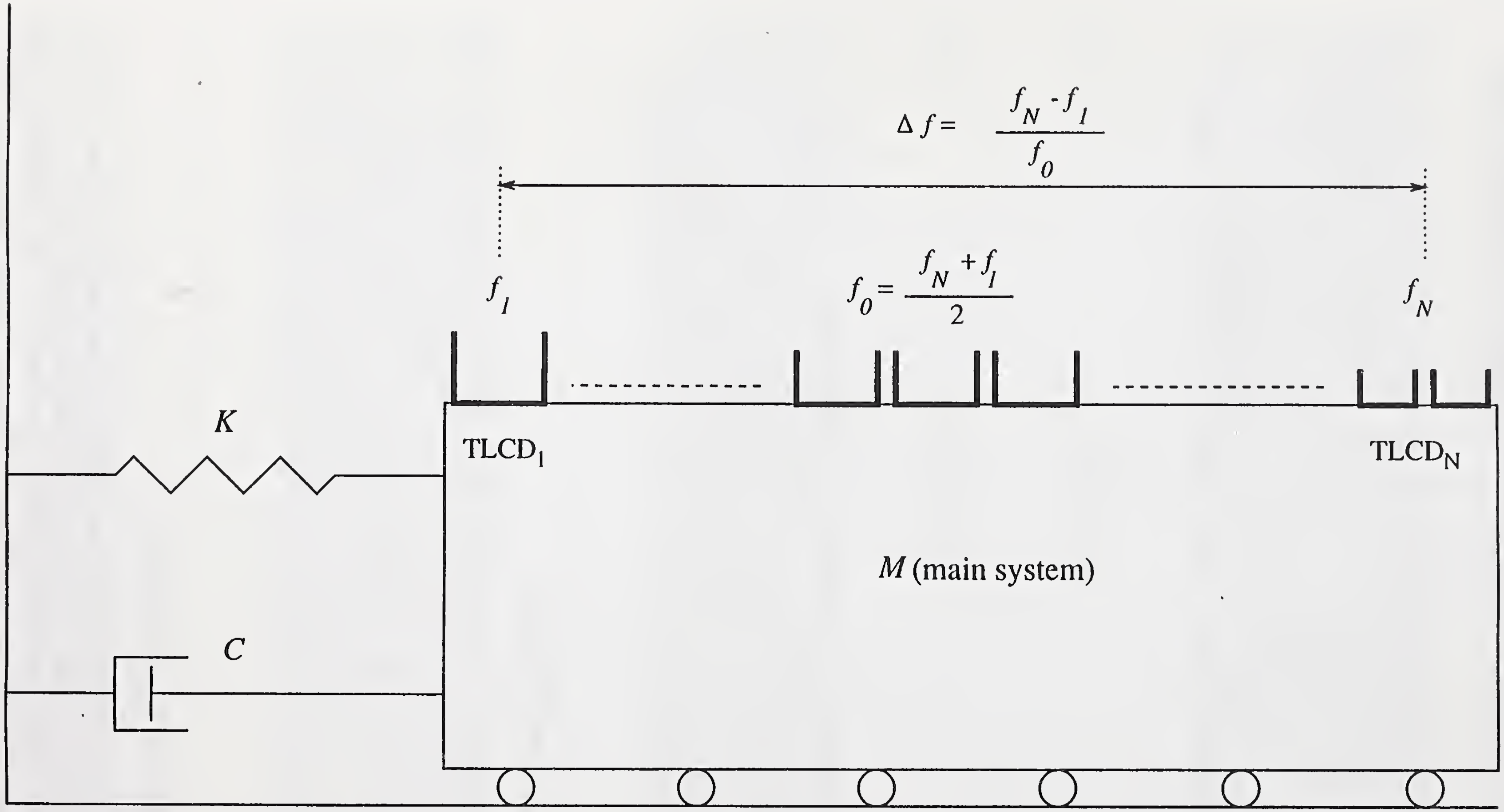


Figure 4.1 Multiple tuned liquid column damper mounted on a main structure

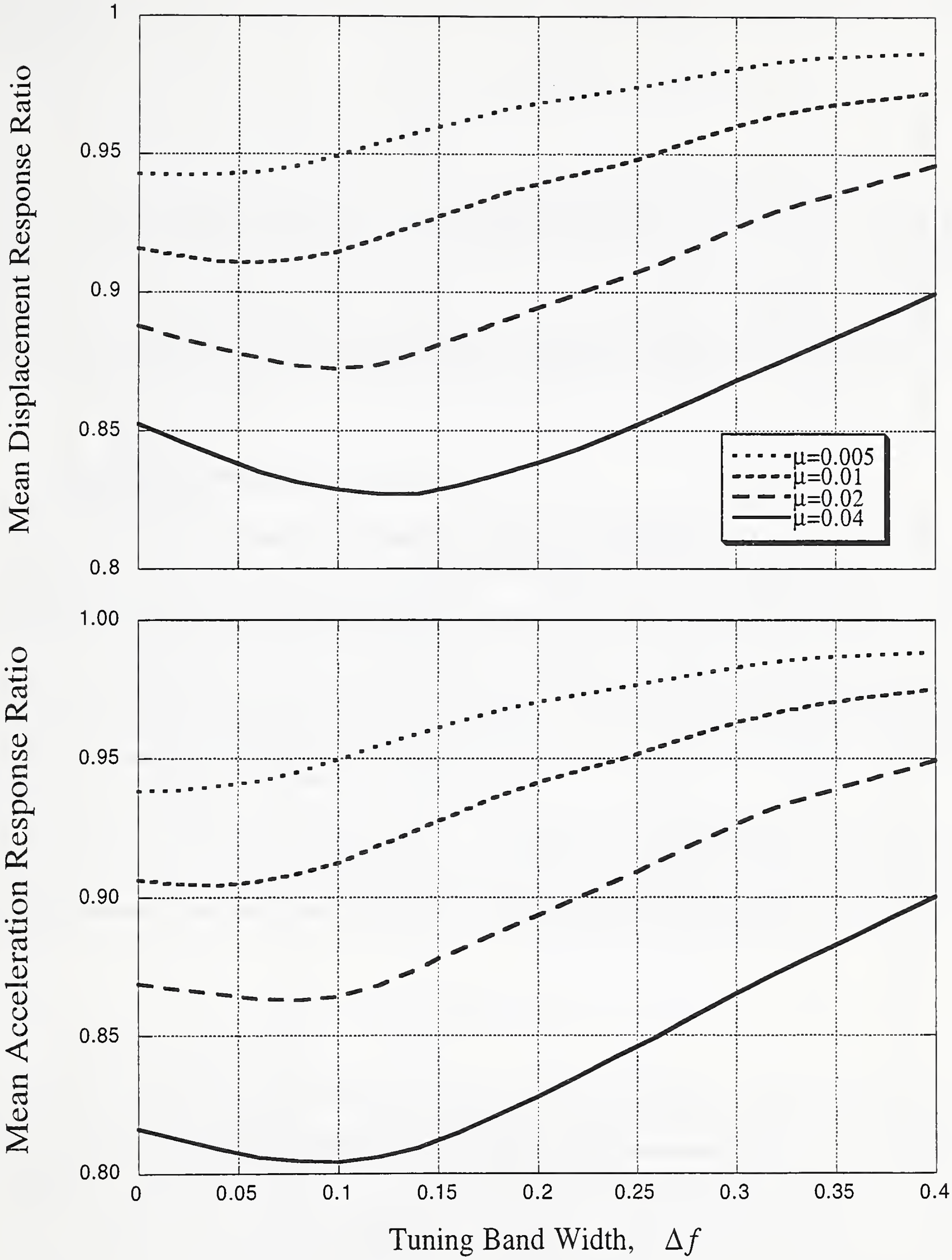


Figure 4.2 Variation of mean response ratios with tuning band width Δf

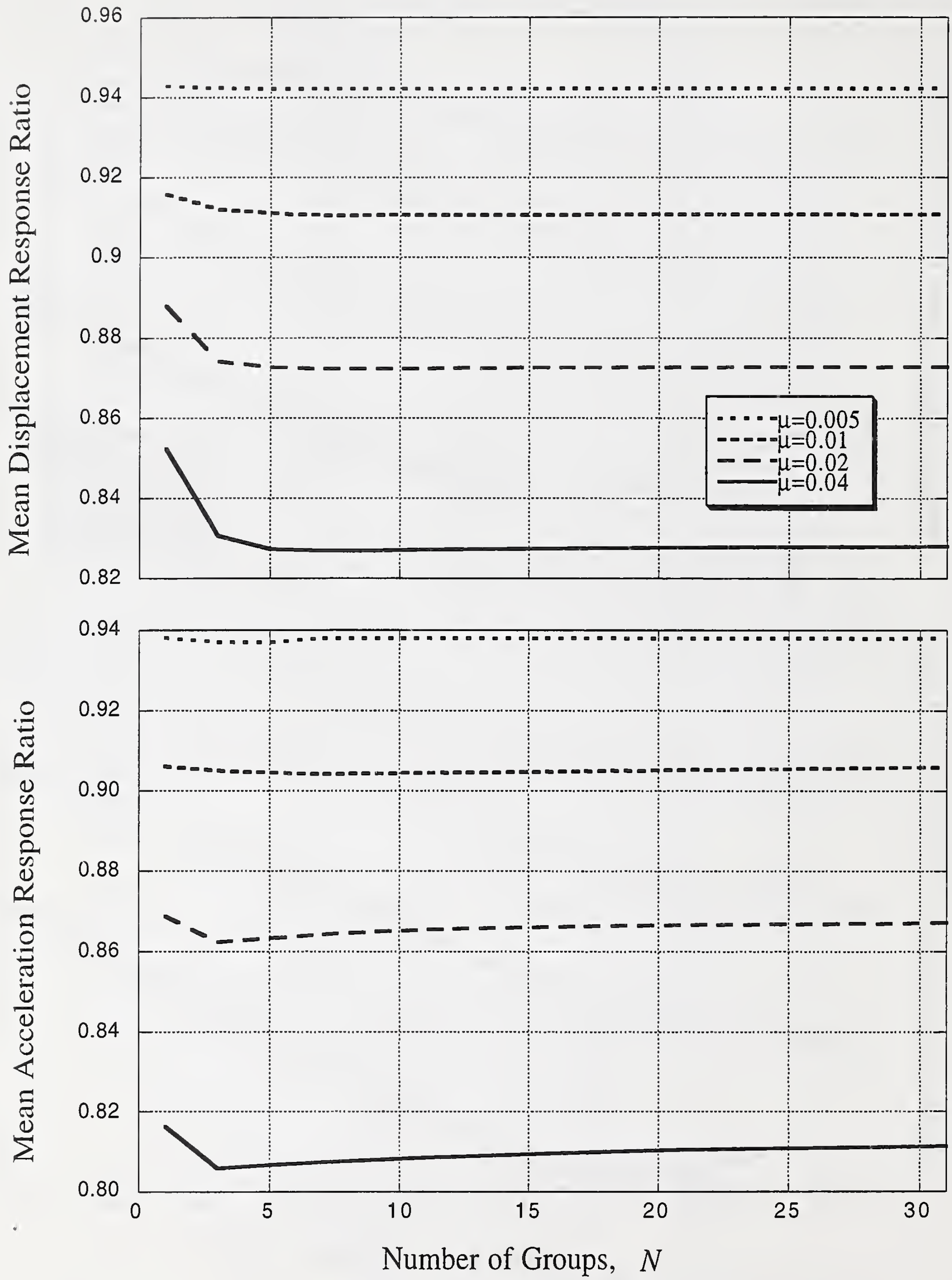


Figure 4.3 Variation of mean response ratios with group number N

the optimum. The figure shows that for small mass ratios, there is no advantage in selecting MTLCDs over STLCDs.

4.3 Optimum Central Tuning Ratio f_0

To determine the optimum central tuning ratio f_0, the same SDOF structure with five TLCD groups and the optimum bandwidths Δf determined from figure 4.2 was considered. The central tuning ratio f_0 was varied from 0.8 to 1.2 with increments of 0.1. The mean displacement and acceleration response ratios for different mass ratios μ computed using the 72 accelerograms are shown in figure 4.4. The plots show that the best response reduction is obtained at a central tuning ratio of approximately 1.0 indicating that for optimum performance, the central frequency of a MTLCD should be tuned to the natural frequency of the structure.

4.4 Selection of Optimum Parameters

From the previous analyses, the selection of MTLCD parameters may be summarized as follows: after selecting the mass ratio μ, the head loss coefficient δ and consequently the orifice opening for all units can be determined similar to STLCDs. The mass ratio is also used to determine the optimum tuning bandwidth Δf. Based on the results of this study, Δf should be 0.125, 0.10, 0.05, and 0.025 for mass ratios μ = 0.04, 0.02, 0.01, and 0.005, respectively. Using five TLCD groups (each TLCD group may contain several units) with a central frequency tuned to that of the structure, the tuning ratio f_i for each group can be determined from equations (4.1) and (4.2) and the liquid lengths L_i from equation (3.1). Using α=0.8, the tube width B_i can be determined. The individual TLCD units in each group should have the same cross-sectional area computed from the liquid mass required.

The procedure was used to select the MTLCD parameters for SDOF structures with periods between 0.1 s to 3.0 s with increments of 0.1 s, a damping ratio of 0.02, and mass ratios of 0.005, 0.01, 0.02, and 0.04. The mean displacement and acceleration response ratios of the structures to the 72 accelerograms scaled to a peak ground acceleration 0.25g are shown in figure 4.5.

4.5 Robust Performance

Comparing the mean displacement and acceleration response ratios for structures with STLCDs (Fig. 3.6), and MTLCDs (Fig. 4.5), one observes only a slight improvement in the displacement and acceleration responses with MTLCDs. Similar observations have been made by Yamaguchi and Harnpornchai (1993) for multiple tuned mass dampers and by Fujino and Sun (1993) for multiple tuned liquid dampers. In both those studies, multiple TMDs and TLCDs proved to be robust (less sensitive) to changes in structural parameters and external excitations. To demonstrate the robustness of MTLCDs over STLCDs, a SDOF structure with 2 percent damping with an assumed period of 1.0 s is selected. Suppose the correct stiffness of the structure corresponds to a period other than 1.0 s, say for example 0.95 s. A STLCD and a MTLCD, each with a mass ratio of 0.04 were selected using the assumed stiffness. The analysis of the structure with STLCD and MTLCD subjected to the S90W component of the El Centro accelerogram, the Imperial Valley earthquake, 1940, scaled to a maximum ground

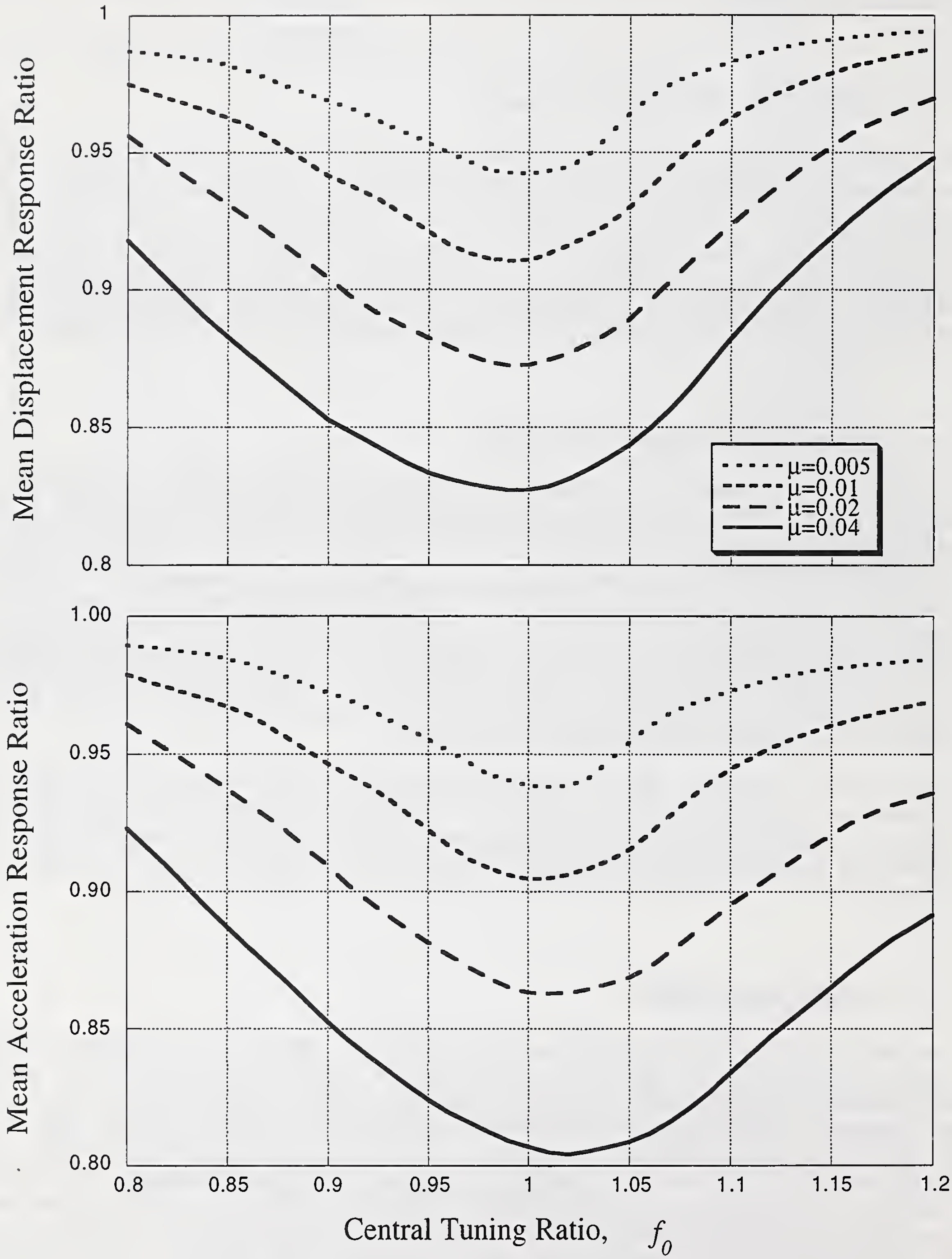


Figure 4.4 Variation of mean response ratios with central tuning ratio f_o

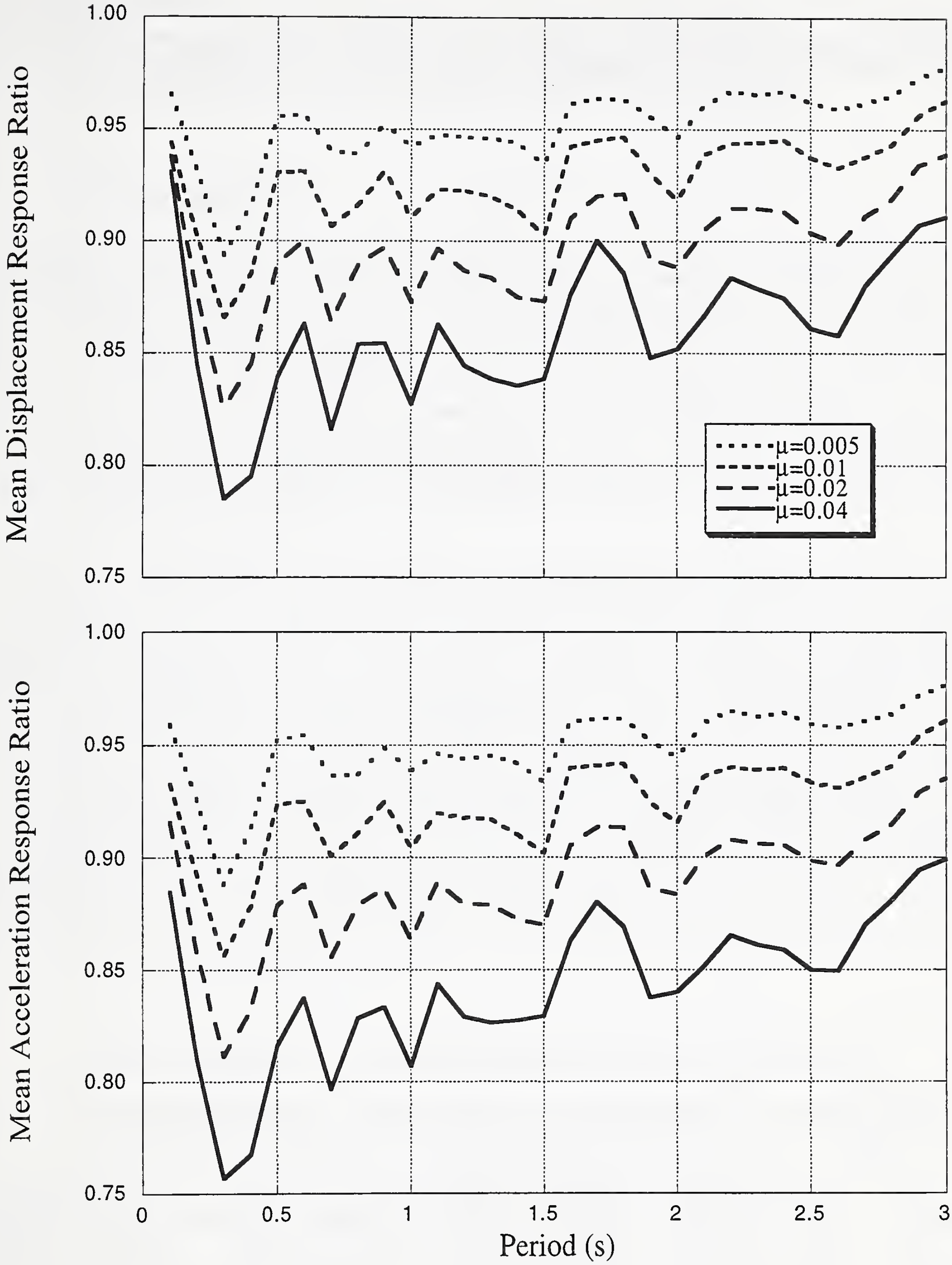


Figure 4.5 Mean response ratios for SDOF structures with MTLCDs

acceleration of $0.25g$ shows that the maximum relative displacement and absolute acceleration are 99.02 mm and $0.435g$ for the structure with STLCD, and 88.77 mm and 0.390 g for the structure with MTLCD; illustrating the robustness of MTLCDs over STLCDs.

5. EXAMPLES

Two examples are presented to show the selection of single and multiple tuned liquid column dampers and demonstrate their performance under different seismic excitations.

5.1 Simple Bridge Model

A long-span box-girder concrete bridge is modeled as a SDOF system with a mass M = 1x10^6 kg, natural period T = 2 s, and damping ratio β = 0.02. The bridge is to be designed for an expected ground acceleration of 0.25 g. Tuned liquid column dampers are attached to the inside of the box girder to reduce the horizontal movement of the bridge. The mass ratio is assumed to be 0.04. The selection of the parameters for the STLCD is as follows: for this mass ratio, the tuning ratio and the head loss coefficient are obtained from equations (3.3) and (3.7) as f = 0.952 and δ = 0.573, respectively. The tuning ratio is used to compute the liquid length L = 2.2 m from equation (3.1) and the head loss coefficient is used to find the orifice opening ratio as 0.75 (Blevins, 1984). Using α = 0.8 as suggested previously, the tube width B will be 1.76 m. To achieve the required mass ratio, 600 tubes, each with a cross-sectional area of 0.03 m^2, filled with water may be used.

If one were to use MTLCD, five TLCD groups would be selected. Using Δf = 0.125 and f_0 = 1 from figures 4.2 and 4.4, respectively, the tuning ratios f_i from equations (4.1) and (4.2) for the five groups would be 1.065, 1.0325, 1.0, 0.9675, and 0.935. The corresponding liquid lengths L_i are 1.75, 1.86, 1.99, 2.13, and 2.27 m. To achieve a mass ratio of 0.04 with water, a total of 100 TLCD units with a cross-sectional area of 0.04 m^2 for each tube must be used for each of the five groups. The orifice opening and the tube width to liquid length ratio are the same as those for the STLCD. The responses of the bridge with no control, with STLCD, and with MTLCD to the following ground excitations: the S90E component of El Centro, the Imperial Valley earthquake, 1940; the S69E component of Taft Lincoln School Tunnel, Kern County earthquake, 1952; the N40W component of Cholame, Shandon, California Array # 12, the Parkfield earthquake, 1966; and the S74W component of Pacoima Dam, the San Fernando Earthquake, 1971; all scaled to a peak ground acceleration of 0.25 g are presented in table 5.1. The table shows that the responses with STLCDs and MTLCDs are nearly identical. Reductions of up to 47 percent in the relative displacements and absolute accelerations are observed when TLCDs are used.

Table 5.1 Response of the simplified bridge model with and without control

	El Centro, 1940		Taft, 1952		Cholame, 1966		Pacoima Dam, 1971	
Control	x_{max} m	a_{max} g	x_{max} m	a_{max} g	x_{max} m	a_{max} g	x_{max} m	a_{max} g
None	0.364	0.367	0.147	0.148	0.333	0.336	0.059	0.059
STLCD	0.194	0.190	0.114	0.117	0.259	0.268	0.053	0.054
MTLCD	0.200	0.196	0.115	0.117	0.257	0.261	0.053	0.054

5.2 Ten-Story Structure

A ten-story structure with an assumed damping ratio of 0.02 in the first mode is to be designed for a peak ground acceleration of 0.4 *g*. The story masses and column stiffnesses from the top to bottom are: {98, 107, 116, 125, 134, 143, 152, 161, 170, 179}x10^3 kg and {34.31, 37.43, 40.55, 43.67, 46.79, 49.91, 53.02, 56.14, 59.26, 62.47}x10^3 kN/m, respectively. The structure has a fundamental natural frequency of 0.5 Hz. Two cases, one with STLCD and another with MTLCD attached to the top floor are considered. The selection of parameters is the same as before except that the mass ratio is computed as the ratio of the liquid mass to the generalized mass for the fundamental mode for a unit modal participation factor; i.e.,

$$\mu = \frac{\rho AL}{\phi_1^T [M] \phi_1} \tag{5.1}$$

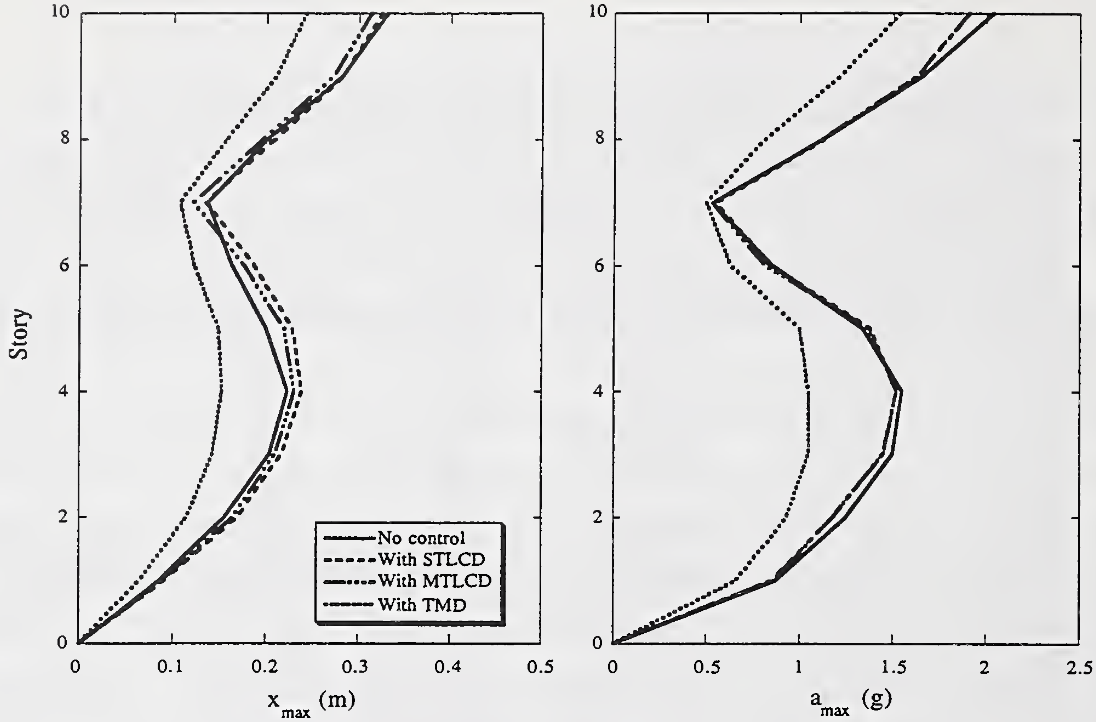
where [M] is the structure mass matrix and ϕ_1 the fundamental mode shape normalized to have a unit participation factor. For the structure considered herein, the generalized mass for the fundamental mode is 1109 x 10^3 kg. If the STLCD and MTLCD are designed for a mass ratio of 0.04, the liquid mass would be 44.36 x 10^3 kg which is equal to 0.032 of the total structural mass and less than 0.25 of the first floor mass. For the STLCD, 800 units, each with a liquid length of 2.2 m and a cross-sectional area of 0.025 m^2 may be used. For the MTLCD, five groups, each with 175 units would be selected. Each unit would have a cross-sectional area of 0.025 m^2 and liquid lengths of 1.75, 1.86, 1.99, 2.13, and 2.27 m. The peak ground acceleration of 0.4*g* results in a head loss coefficient δ = 0.358, equation (3.7). The structure with and without TLCDs was subjected to the 90 degree component of the Corralitos Eureka Canyon Road accelerogram and the 90 degree component of the Capitola Fire Station accelerogram from the Loma Prieta earthquake of October 17, 1989; and the 90 degree component of the Santa Monica City Hall Grounds accelerogram and the 90 degree component of the Arleta Nordhoff Avenue Fire Station accelerogram from the Northridge earthquake of January 17, 1994; each scaled to a peak ground acceleration of 0.4 *g*. The results of the analyses, summarized in table 5.2, show a reduction of up to 40 percent in the displacement and 24 percent in the acceleration of the top floor. Both STLCDs and MTLCDs result in approximately the same response reduction.

This structure was also analyzed with a tuned mass damper attached to the top floor. It is assumed that the TMD has the same mass ratio as that of the TLCD (μ = 0.04). The method presented by Sadek *et al.* (1996) was used to select the TMD parameters. The tuning ratio of the TMD is 0.994 and the damping ratio 0.293. The responses of the structure with no control and with STLCD, MTLCD, and TMD to the above ground excitations are plotted in figure 5.1. The plots show that the performance of both TMDs and TLCDs are comparable. Table 5.2 and figure 5.1 show that for some records (Capitola and Arleta), both devices result in substantial reductions in the response while for other records (Corralitos and Santa Monica), the reductions are not as significant, underscoring that the performance of TMDs and TLCDs is influenced by the frequency content of the excitation.

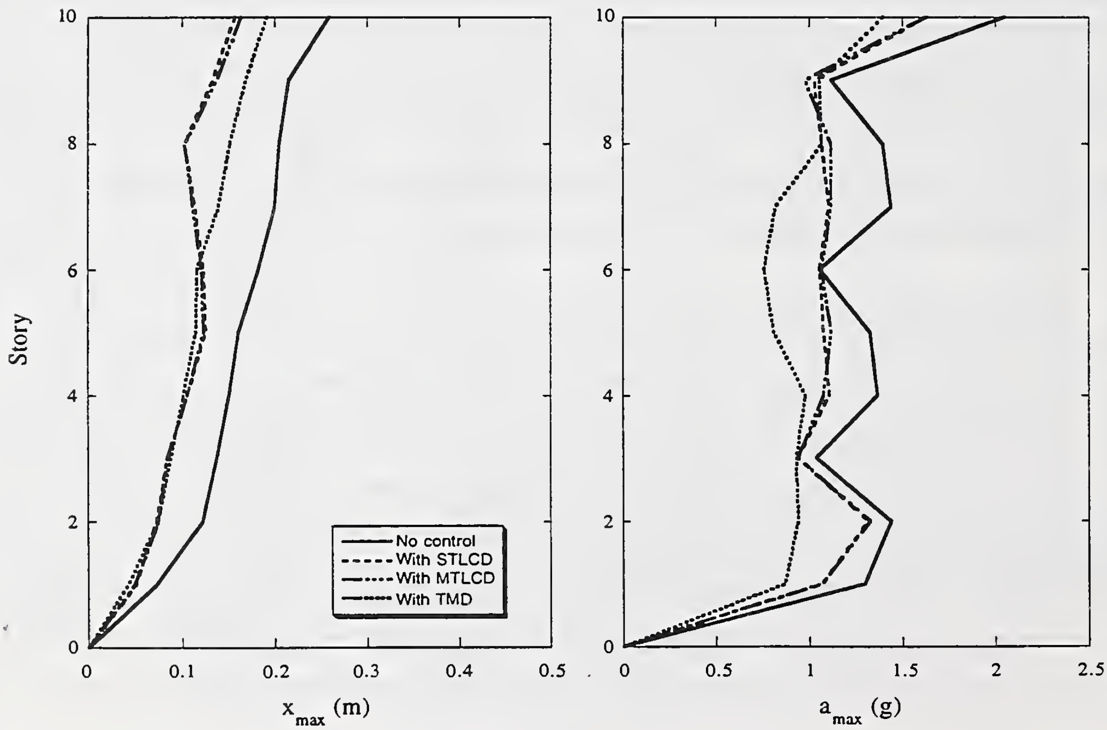
Table 5.2 Responses of the ten-story building with and without control

Level	Corralitos, 1989						Capitola, 1989					
	No Control		STLCD		MTLCD		No Control		STLCD		MTLCD	
	x_{max} *m*	a_{max} *g*	x_{max} *m*	a_{max} *g*	x_{max} *m*	a_{max} *g*	x_{max} *m*	a_{max} *g*	x_{max} *m*	a_{max} *g*	x_{max} *m*	a_{max} *g*
Top	0.331	2.04	0.325	1.91	0.314	1.91	0.258	2.05	0.156	1.63	0.163	1.63
9	0.282	1.66	0.283	1.63	0.272	1.63	0.215	1.12	0.133	1.03	0.137	0.98
8	0.200	1.12	0.208	1.13	0.195	1.12	0.205	1.40	0.103	1.07	0.103	1.12
7	0.136	0.53	0.134	0.55	0.121	0.53	0.200	1.44	0.114	1.11	0.112	1.12
6	0.162	0.85	0.186	0.84	0.175	0.81	0.182	1.06	0.123	1.06	0.121	1.07
5	0.200	1.34	0.228	1.38	0.219	1.37	0.160	1.33	0.125	1.08	0.123	1.12
4	0.223	1.55	0.238	1.52	0.230	1.52	0.150	1.37	0.106	1.11	0.106	1.08
3	0.204	1.50	0.217	1.45	0.210	1.45	0.137	1.04	0.084	0.94	0.084	0.94
2	0.155	1.25	0.169	1.18	0.164	1.18	0.122	1.44	0.072	1.32	0.074	1.33
1	0.086	0.87	0.091	0.85	0.089	0.86	0.072	1.30	0.050	1.07	0.049	1.07

Level	Santa Monica, 1994						Arleta, 1994					
	No Control		STLCD		MTLCD		No Control		STLCD		MTLCD	
	x_{max} *m*	a_{max} *g*	x_{max} *m*	a_{max} *g*	x_{max} *m*	a_{max} *g*	x_{max} *m*	a_{max} *g*	x_{max} *m*	a_{max} *g*	x_{max} *m*	a_{max} *g*
Top	0.219	1.04	0.217	0.92	0.217	0.92	0.463	1.90	0.309	1.44	0.279	1.43
9	0.201	0.71	0.198	0.71	0.189	0.70	0.443	1.20	0.292	1.21	0.252	1.18
8	0.182	0.81	0.179	0.69	0.178	0.67	0.414	1.38	0.262	0.97	0.214	0.98
7	0.170	0.66	0.162	0.68	0.171	0.67	0.356	1.00	0.215	0.87	0.184	0.87
6	0.164	0.64	0.153	0.69	0.160	0.65	0.338	1.03	0.162	0.87	0.168	0.92
5	0.146	0.81	0.130	0.66	0.141	0.67	0.311	1.40	0.160	1.20	0.174	1.20
4	0.129	0.69	0.107	0.67	0.115	0.67	0.275	1.32	0.163	0.99	0.166	1.01
3	0.103	0.63	0.085	0.65	0.090	0.64	0.218	1.02	0.148	1.11	0.144	1.09
2	0.074	0.59	0.063	0.58	0.068	0.59	0.154	1.13	0.116	1.16	0.102	1.14
1	0.042	0.72	0.039	0.70	0.039	0.70	0.083	1.05	0.064	0.93	0.058	0.93

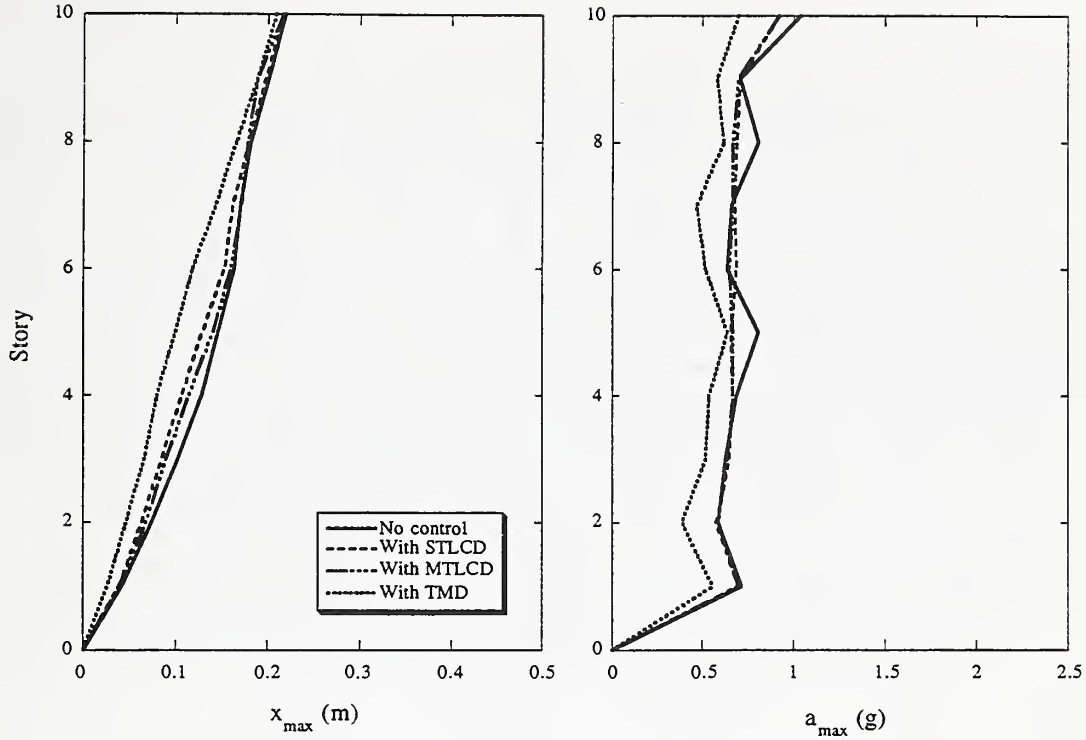


(a) Corralitos, 1989

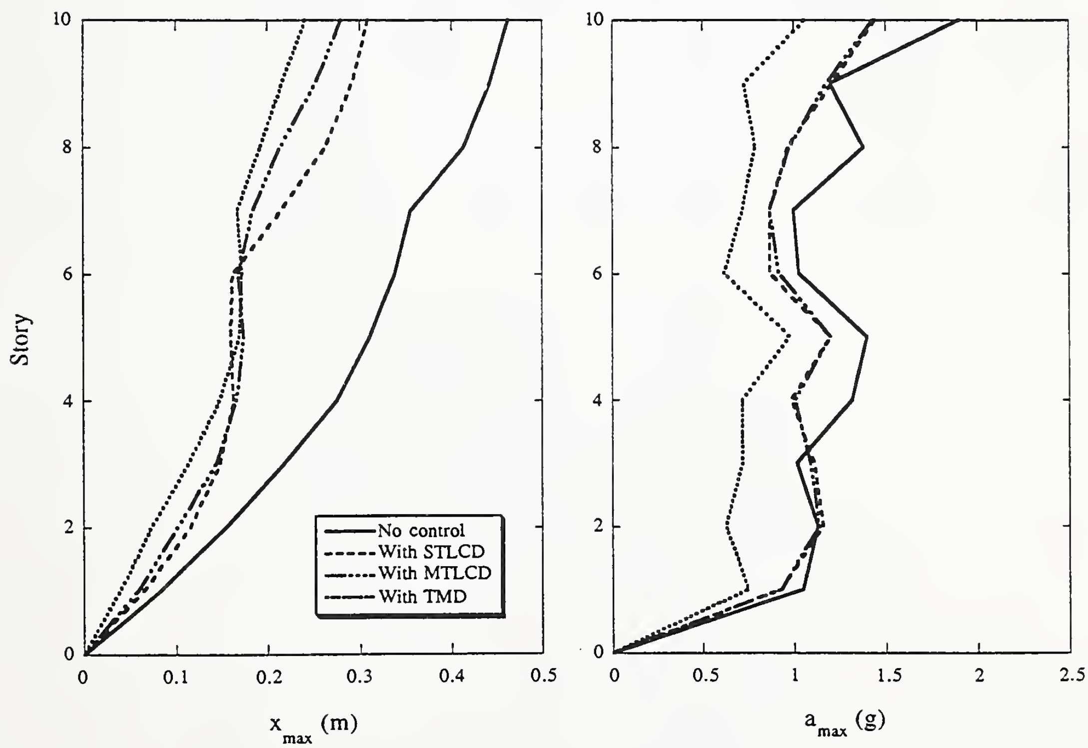


(b) Capitola, 1989

Figure 5.1 Peak responses of the ten-story building with no control and with STLCD, MTLCD, and TMD to four ground excitations



(c) Santa Monica, 1994



(d) Arleta, 1994

Figure 5.1 Continued

6. CONCLUSIONS

The objective of this study was to determine the optimum parameters for tuned liquid column dampers (TLCDs) for seismic applications. The optimum parameters for single tuned liquid column dampers (STLCDs): tuning, damping, and liquid length to tube width ratios; and for multiple tuned liquid column dampers (MTLCDs): central tuning ratio, tuning bandwidth, and number of TLCD groups are determined from a deterministic response analysis of SDOF structures to 72 earthquake accelerograms. The parameters were used to compute the response of several single-degree-of-freedom and multi-degree-of-freedom structures with single and multiple TLCDs to different earthquake excitations. The results indicate that using the optimum parameters results in displacement and acceleration response reductions of up to 47 percent. The study shows that while multiple tuned liquid column dampers are not necessarily superior to single tuned liquid column dampers, they are robust with respect to errors in estimating the structural parameters. Comparisons with tuned mass dampers indicate that both devices are comparable in reducing the response of structures. Design examples for STLCD and MTLCD used in a bridge modeled as a SDOF structure and a ten-story building modeled as a MDOF structure are presented to illustrate the selection of the parameters and demonstrate the performance of the STLCDs and MTLCDs under different ground excitations. The performance of tuned liquid column dampers was also compared with that of tuned mass dampers where it was found that both devices result in approximately the same reductions in the response. These reductions, however, are influenced by the frequency content of the excitations.

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APPENDIX A. EARTHQUAKE RECORDS USED IN THE STATISTICAL STUDY

Earthquake	Mag.	Station Name	Source Distance (km)	Comp.	Peak Accel. (g)
Imperial Valley 05/18/1940	6.7	El Centro Valley Irrigation District	11.6	S00E S90W	0.348 0.214
Northwest California 10/07/1951	5.8	Ferndale City Hall	56.3	S44W N46W	0.104 0.112
Kern County 06/21/1952	7.7	Pasadena - Caltech Athenaeum	127.0	SOOE S90W	0.047 0.053
		Taft Lincoln School Tunnel	41.4	N21E S69E	0.156 0.179
		Santa Barbara Court House	88.4	N42E S48E	0.089 0.131
		Holywood Storage Basement	120.4	SOOW N90E	0.055 0.044
Eureka 12/21/1954	6.5	Ferndale City Hall	40.0	N44E N46W	0.159 0.201
San Francisco 03/22/1957	5.3	San Francisco Golden Gate Park	11.2	N10E S80E	0.083 0.105
Hollister 04/08/1961	5.7	Hollister City Hall	22.1	S01W N89W	0.065 0.179
Borrego Mountain 04/08/1968	6.4	El Centro Valley Irrigation District	67.3	S00W S90W	0.130 0.057
Long Beach 03/10/1933	6.3	Vernon CMD Bldg.	50.5	S08W N82W	0.133 0.155
Lower California 12/30/1934	7.1	El Centro Valley Irrigation District	66.4	S00W S90W	0.160 0.182
Helena Montana 10/31/1935	6.0	Helena, Montana Carrol College	6.2	S00W S90W	0.146 0.145
1st Northwest California 09/11/1938	5.5	Ferndale City Hall	55.2	N45E S45E	0.144 0.089
Northern California 09/22/1952	5.2	Ferndale City Hall	43.1	N44E S46E	0.054 0.076
Wheeler Ridge, California 01/12/1954	5.9	Taft Lincoln School Tunnel	42.8	N21E S69E	0.065 0.068
Parkfield, California 06/27/1966	5.6	Chalome, Shandon, California Array # 5	56.1	N05W N85E	0.355 0.434
		Cholame, Shandon, California Array # 12	53.6	N50E N40W	0.053 0.064
		Temblor, California # 2	59.6	N65W S25W	0.269 0.347

Earthquake records (continued)

Earthquake	Mag.	Station Name	Source Distance (km)	Comp.	Peak Accel. (g)
San Fernando 02/09/1971	6.4	Pacoima Dam	7.3	S16E S74W	1.172 1.070
		8244 Orion Blvd. Los Angeles, California	21.1	N00W S90W	0.255 0.134
		250 E First Street Basement, Los Angeles	41.4	N36E N54W	0.100 0.125
		Castaic Old Ridge Route	29.5	N21E N69W	0.315 0.270
		7080 Hollywood Blvd. Basement, Los Angeles	33.5	N00E N90E	0.083 0.100
		Vernon CMD Bldg.	48.0	N83W S07W	0.107 0.082
		Caltech Seismological Lab., Pasadena	34.6	S00W S90W	0.089 0.193
Loma Prieta 10/17/1989	7.1	Corralitos - Eureka Canyon Road	7.0	90 deg. 0 deg.	0.478 0.630
		Capitola - Fire Station	9.0	90 deg. 0 deg.	0.398 0.472
		Foster City - Redwood Shores	63.0	90 deg. 0 deg.	0.283 0.258
		Monterey - City Hall	49.0	90 deg. 0 deg.	0.062 0.070
		Woodside - Fire Station	55.0	90 deg. 0 deg.	0.081 0.081
Northridge 01/17/1994	6.7	Arleta Nordhoff Ave. - Fire Station	9.9	90 deg. 360 deg.	0.344 0.308
		New Hall - LA County Fire Station	19.8	90 deg. 360 deg.	0.583 0.589
		Pacoima Dam - Down Stream	19.3	265 deg. 175 deg.	0.434 0.415
		Santa Monica - City Hall Grounds	22.5	90 deg. 360 deg.	0.883 0.370
		Sylmar - County Hospital Parking Lot	15.8	90 deg. 360 deg.	0.604 0.843

APPENDIX B. LIST OF SYMBOLS

a	Peak ground acceleration
a_{max}	Maximum absolute acceleration
A	Cross sectional area of the liquid damper
B	Tube width
c_p	Equivalent damping coefficient of TLCD
f	Tuning ratio of STLCD
f_0	Central frequency ratio of MTLCDs
g	acceleration of gravity
L	Liquid column length
M	Mass of an SDOF structure or the generalized mass in an MDOF structure
[M]	Mass matrix
N	Number of groups in a MTLCD
T	Natural Period
v	Peak ground velocity
x	Displacement of the main structure
$\ddot{x}_g$	Ground acceleration
x_{max}	Maximum relative displacement
y	Elevation change of the liquid surface
α	Tube width to liquid length ratio
β	Damping ratio of structure
δ	Coefficient of head loss of the damper
Δf	Frequency bandwidth of MTLCDs
η	Constant that depends on μ and β
ϕ_1	Fundamental modal shape
μ	Mass ratio of TLCD
ρ	Liquid density
$\sigma_{\dot{y}}$	Standard deviation of the liquid elevation velocity
ω_o	Natural or fundamental frequency of the structure
ω_t	Natural frequency of TLCD
ξ	Equivalent damping ratio of TLCD